EFFECTS OF COLD WEATHER ON DURABILITY OF CFRP STRENGTHENED CIRCULAR HOLLOW STEEL MEMBERS

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ABSTRACT

Tubular members have become progressively more popular due to excellent structural properties, aesthetic appearance, corrosion and fire protection capability. However, a large number of such structures are found structurally deficient due to reduction of strength when they expose to severe environmental conditions such as marine environment, cold and hot weather. Hence strengthening and retrofitting of structural members are in high demands. In recent times Carbon Fibre Reinforced Polymers (CFRP) composites appears to be an excellent solution to enhance the load carrying capacity and serviceability of steel structures because of its superior physical and mechanical properties. However, the durability of such strengthening system under cold environmental condition has not yet been well documented to guide the engineers. This paper presents the findings of a study conducted to enhance the bond durability of CFRP strengthened steel tubular members by treating steel surface using epoxy based adhesion promoter under cold weather subjected to bending. The experimental program consisted of six number of CFRP strengthened specimens and one bare specimen. The sand blasted surface of the three specimens to be strengthened was pre-treated with MBrace primer and other three were remained untreated and then cured under ambient temperature and cold weather (3^{o}C) for three and six months period of time. The beams were then loaded to failure under four point bending. The structural response of each specimen was predicted in terms of failure mode, failure load and mid-span deflection. The research findings show that the cold weather immersion had an adverse effect on durability of CFRP strengthened structures. Moreover, the epoxy based adhesion promoter was found to enhance the bond durability in elastic range.

KEYWORDS

Tubular steel member, CFRP, strengthening, durability, cold weather, surface pre-treatment.

INTRODUCTION

The tubular shape structural members generally show excellent properties with regard to bending in all directions. There has been wide application of hollow sections as structural members in bridges. In buildings, hollow sections are mainly used for columns, facade and lattice girders or space frames for roofs. The hollow sections are also used in jacket-type structures to form a space frame. A large number of such structures made of hollow section are found structurally deficient due to strength deterioration and corrosion when they experience severe environmental conditions such as marine environment, cold and hot weather. By considering economical feasibility, aesthetic appearance, high strength and stiffness-to-weight ratios and excellent resistance to corrosion, degradation and fatigue, carbon fibre reinforced polymer (CFRP) composites appears to be an excellent solution to strengthen structural steel structures. Number of studies has been conducted on bond behaviour of CFRP strengthened steel structure (Fawzia 2013; Fawzia *et al.* 2010; Fawzia *et al.* 2007). Durability of CFRP strengthened concrete structures has also been studied comprehensively by Gamage *et al.* (2009) and Smith *et al.* (2005) recently. However, till now a few number of literatures are available on durability of CFRP strengthened steel structures under natural and simulated sea water and elevated temperature subjected to bending and tension (Seica and Packer 2007; Al-Shawaf *et al.* 2008; Dawood and Rizkalla 2010). Moreover, to the author’s knowledge, no study has been found on durability of CFRP strengthened tubular steel members conditioned under cold weather and tested to determine residual flexural capacity and stiffness at ambient temperature. Therefore, this paper presents an experimental study on durability of CFRP strengthened steel tubular flexural member conditioned under cold weather.

EXPERIMENTAL INVESTIGATION

Material Properties

The materials used in this study were steel tubes, CFRP, adhesives and adhesion promoter. The average yield stress and ultimate strength of steel tube were found 327 MPa and 383 MPa respectively by coupon test. The CFRP was of the type CF130 specified by BASF construction chemicals Australia Pty Ltd having manufacturer provided elastic modulus of 227 GPa and nominal tensile strength of 3800 MPa. The adhesive was two-part impregnation resin MBrace saturant with tensile strength, compressive strength and elastic modulus 50 MPa, 80 MPa and 3000 MPa respectively. The tensile strength and elastic modulus of MBrace primer were 12 MPa and 700 MPa as well.

Test Specimens

A total of seven specimens were cut into required size. All specimens were identical in their dimensions: circular cross-sections of 101.6 mm outer diameter and 4.0 mm thickness. Depending on test facility at laboratory, the length of the circular member was chosen 1300 mm and the effective span was considered 1200 mm for a four-point bending test as shown in Figure 1.

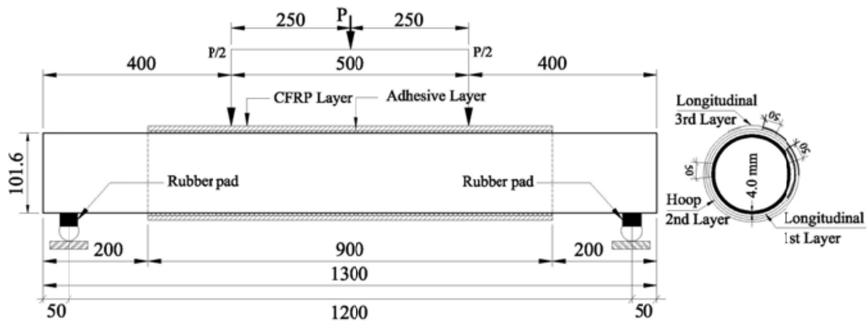

Figure 1. Specimen details

Specimen Preparation

After cutting the specimens into desired dimension, the surface of the tubes to be strengthened was prepared by sand blasting to achieve high energy surface for well bonding as shown in Figure 2. Then the week layer, deposited dust and grease were removed by paper towel impregnated with acetone. Adhesion promoter was then applied on acetone cleaned surface for three specimens prior to applying epoxy adhesive. The two part epoxy adhesive was mixed properly and applied on pretreated steel surface during its pot life according to manufacturer guidelines. The first layer of CFRP fabrics (MBRACE CF 130 fibre system) oriented longitudinally to the length of the beam was directly applied into uncured adhesive applied on the substrate. A rib roller was used to press the fabric against the substrate until visual signs of adhesives were observed bleeding through the fabric. The rib roller or squeegee should only be run along the direction of the primary fibres in the fabric and to remove air bubbles entrapped in adhesive layer. Then the first layer was confined with a second layer with the fibres oriented transversely to the tube axis. The circumferential layer (second layer) was used to confine the longitudinal layers whilst subjected to compressive stresses during bending. For the application of third layer of CFRP fabrics, the same procedure was performed as first layer. The whole procedure was done wet on wet surface which implies the top surface of the bottom layer remains still sticky. To achieve good quality bond between CFRP and steel as well as between CFRP itself, masking tape was wrapped around the strengthened area and kept for a period of at least 24 hours and then it was removed as shown in Figure 3. Two specimens were control specimen for both treated and untreated surface and one specimen is without CFRP strengthened which was called bare specimen. There were four (two specimens from treated and untreated category) specimens cured for 3 and 6 months under constant 3^{o}C temperature.

Figure 2. Sand blasted surface

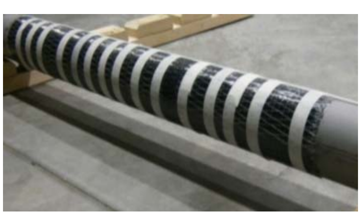

Figure 3. Curing with masking tape for 24 hours

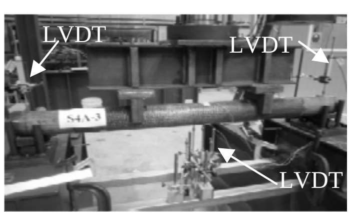

Figure 4. Experimental set-up

Test Set-up and Instrumentation

A total of seven specimens including bare one were tested under four point bending test with simply supported condition on two rectangular rubber pads (25mm thick). The test set-up is shown in Figure 4. The test was carried out using a 230 kN controlled MTS actuator applying displacement control 'static compression load' at a constant rate. The load was continued up to the failure. Instrumentation provided at this stage four linear variable differential transformer (LVDTs) were installed to measure displacements as shown in Figure 4. Two LVDTs were fixed at mid-span on each side of the beam to measure the average deflection at the mid-depth. Another two LVDTs were mounted on top of the support to measure support displacement. The actual beam deflection was then calculated by deducting support displacement from mid-span displacement. The data from LVDTs were recorded by computer programmed LABVIEW software at 5 second time interval. The failure load and actuator displacement were recorded accordingly by computer programmed station manager software connected to MTS controller.

EXPERIMENTAL RESULTS

Failure Mode of the Tested Beams

The tests were carried out by increasing the displacement of the actuator until the deflection continued to increase but there was no increase of load. Typical ductile modes of failure were observed during testing as shown in Figure 5. No serious deboning problems were found in reinforced specimens until the yield load. At failure, the outer fibbers of CFRP fabrics were found to be ruptured by showing distortion over the surface of the compression zone. The failure was occurred for most of the beams due to local buckling failure of the tubular section in the compression zone near the loading point with crushing of fibre layers. The slip between CFRP layers and steel tube was found at failure for each strengthened control as well as conditioned beam. The maximum slip recorded for control beam was 9 mm while this value for conditioned beam was 11 mm. Hence, it can be said that the cold weather has affected the bond behaviour between steel substrate and CFRP composites.

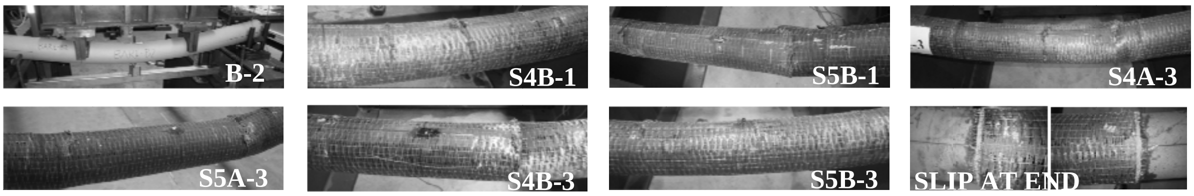

Figure 5. Failure mode of the tested beams

Table 1. Test details, ultimate load and deflection for tested specimens

Exposure condition	Exposure duration	Specimen ID	Surface condition	Ultimate load (kN)	$P_u^{(cs)}$/ $P_u^{(s)}$	Deflection at ultimate load (mm)	Comments
Ambient Temperature	NA	Bare-B2	NA	76.75	-	75.60	Unstrengthened
	+4 weeks	S4B-1	Untreated	94.40	1.23	59.00	Strengthened control
	+4 weeks	S5B-1	Treated	101.70	1.33	16.24	Strengthened control
3° C Temperature	3 Months	S4A-3	Untreated	93.60	1.22	72.20	Strengthened conditioned
	3 Months	S5A-3	Treated	97.00	1.26	47.40	Strengthened conditioned
3° C Temperature	6 Months	S4B-3	Untreated	89.85	1.17	54.00	Strengthened conditioned
	6 Months	S5B-3	Treated	98.43	1.28	32.78	Strengthened conditioned

Effects of CFRP Layers and Adhesion Promoter on Ultimate Strength of Control Beam

The experimental failure loads for all the beams tested are shown in Table 1. The corresponding ratios of ultimate load of the strengthened specimens $P_u^{(cs)}$ relative to bare steel specimen $P_u^{(s)}$ is also listed in Table 1. The results indicate that the CFRP reinforcement helps to increase the ultimate strength through the effective use of the longitudinal fibre strength and restraining action of hoop-oriented fibres. However, the increased load is not tremendous in comparing to the bare specimen. This is because of using compact section and the results are in well agreement with the experimental results for compact section reported by Haedir *et al*. (2009). Figure 6 shows the increment of ultimate load carrying capacity of CFRP externally reinforced CHS members with respect to bare specimen subjected to bending. It can be seen that the strengthening technique applied in the current research for compact section using LHL (one longitudinal + one hoop + one longitudinal layer) combination of CFRP were able to achieve maximum 33% more ultimate load capacity compared to bare specimen. It can also be noted that specimen, S5B-1 withstands higher ultimate load than that of S4B-1. It likely happens due to enhanced bond characteristics by adhesion promoter applied on sand blasted steel surface which is considered as treated surface.

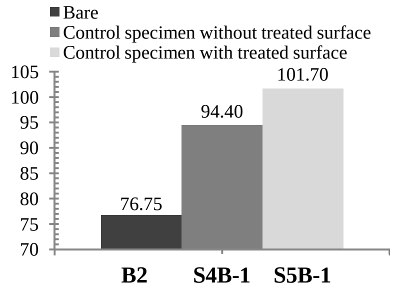

Figure 6. Ultimate strength of bare and strengthened control beams

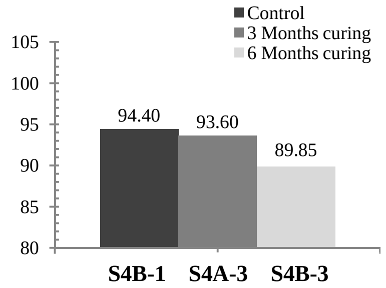

Figure 7. Ultimate strength of conditioned beams (untreated surface)

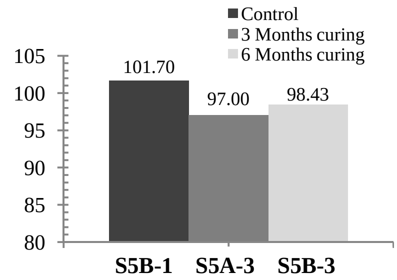

Figure 8. Ultimate strength of conditioned beams (treated surface)

Effects of Cold Weather on Ultimate Strength

All the beams conditioned under cold (3^{o}C) weather, displayed lower ultimate load than that of control specimen cured under ambient temperature as shown in Figure 7. The untreated beam specimens, S4A-3 and S4B-3 show 0.85% and 4.82% lesser strength increment than control beam, S4B-1 for 3 months and 6 months of curing period respectively. However, the epoxy treated beams, S5A-3 and S5B-3 exhibited 4.62% and 3.22% strength reduction with respect to control beam S5B-1 for a period of 3 and 6 months conditioning respectively (Figure 8). Therefore, the reduction of ultimate strength of the conditioned beams implies that the cold weather has adversely affected the ultimate strength of CFRP strengthened steel tubular members. It may happens due to hardening/microcracking of matrix and bond degradation between the interface of steel and CFRP by the effect of prolonged cold weather.

Effects of Surface Pre-treatment on Ultimate Strength

When it is compared the untreated conditioned beams with the surface treated conditioned beams, it can be seen that the beams treated with epoxy based primer have performed better than untreated beams as shown in Figure 8. During 3 months curing period, it can be seen that beam S4A-3 displays lesser flexural capacity than beam S5A-3 treated by epoxy primer. Likewise, beam S5B-3 withstands higher load than untreated beam, S4B-3 after 6 months curing under cold weather. This clearly indicates that the adhesion promoter such as epoxy based MBrace primer is able to enhance the bond between steel and CFRP when the system exposed to cold weather.

Effects of Curing Period on Ultimate Strength

A considerable strength reduction with conditioning period was noticeable from untreated strengthen beams. While for the epoxy treated beams, S5B-3, conditioned for 6 months period of time has shown a slight higher load than that of beam, S5A-3 conditioned for 3 months as shown in Figure 8. This unexpected value may appear due to variation of section dimension which has been confirmed by measuring the outer diameter of strengthened specimens. The recorded outer diameters of strengthen specimens S5A-3 and S5B-3 including CFRP and adhesives are 106.68 mm and 108.25 mm respectively. This variation of dimension may happen due to variation of thickness of adhesive layers.

Mid-Span Deflection

The beams were loaded beyond failure in a displacement control 'static compression load' at 4 mm per minute and data were recorded at 5 second interval. The load-deflection responses for strengthened beams as well as bare specimen are plotted in Figures 9-12, wherein the responses of the strengthened specimens cured in ambient and 3^{o}C temperatures can be compared to that of the reference beam.

Effects of CFRP and surface preparation on stiffness of control beams

Figure 9 shows that both reinforced beams S4B-1 and S5B-1 display lesser deflection than that of bare one starting from around 28 kN load till failure. Since, stiffness is directly related to deflection; it appears that strengthened beams were stiffer than the bare specimen when the contribution of CFRP starts working. Hence, it can be said that the additional stiffness was attributed by the bonded CFRP layers on steel members. It also can be seen that the beam, S5B-1 having epoxy treated surface shows lower deflection starting from about 76 kN load up to failure than that of beam S4B-1 having untreated surface. This was somewhat expected because of the bond enhancement attributed by the epoxy based adhesion promoter.

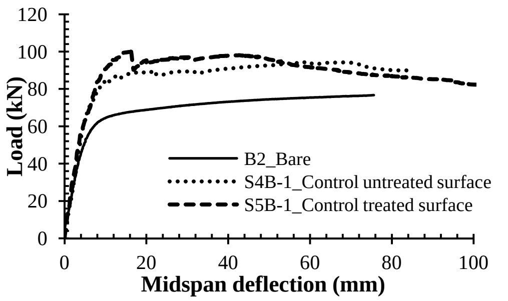

Figure 9. Load-deflection response of strengthened and bare beams

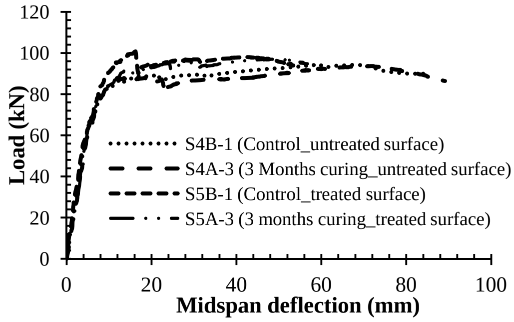

Figure 10. Load-deflection response of conditioned and strengthened control beams

Effect of cold weather on stiffness of strengthened beams

It is clearly seen that all specimens shown in Figure 10 display similar deflection trend and linear-elastic behaviour until around 76 kN load and then the deflection trend has broken and change to inelastic behaviour till failure. The untreated conditioned beam S4A-3 and corresponding control beam S4B-1 show very similar response under increased load and it continues until 18 mm deflection is attained. Beyond that point the conditioned beam exhibits a decrease in stiffness and ultimate load compared to unconditioned beam. Similar deflection phenomenon is observed in epoxy treated conditioned beam S5A-3 and control beam S5B-1 but deflection response was similar until 8 mm. Hence, it can be said that the cold weather has affected adhesive bond performance by making it hardens and weakening the mechanical interlocking of adhesive particles due to formation of microcracking.

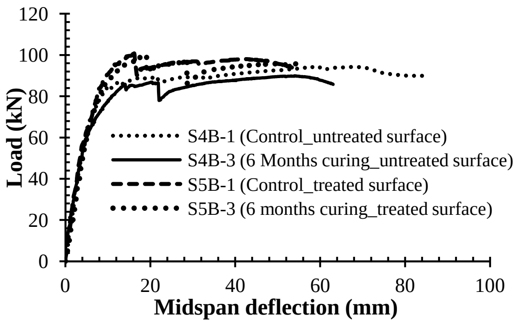

Figure 11. Load-deflection response of conditioned and strengthened control beams

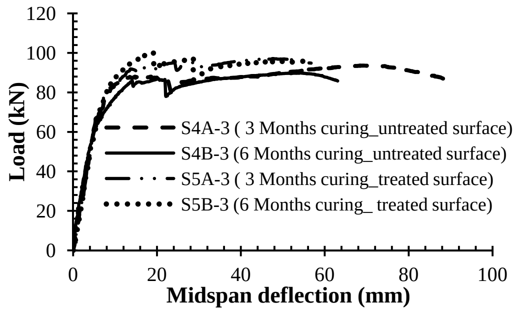

Figure 12. Load-deflection response of conditioned beams

Effect of surface pre-treatment on deflection of conditioned beams

The epoxy treated beams perform better than untreated beams in terms of deflection in plastic region when go under cold weather for a period of three and six months respectively as shown in Figures 10 and 11. Hence, it can be said that adhesion promoter has increased the bond between steel surface and conventional adhesive by increasing the stiffness and ultimate load of the conditioned specimens as well.

Effect of curing period on ultimate strength of strengthened beams

The effect of curing period under cold weather is shown in Figure 12. It can be seen that the curing period has affected the stiffness of the strengthened beams with an exception for an epoxy treated beam S5B-3 cured over six months between deflection limit about 8 mm to 28 mm. This exception may happen due to higher section properties contributed by thicker layer of adhesive which act compositely until this limit. It is also clear that the epoxy treated beams cured under cold weather have shown higher stiffness in plastic range till failure.

PROPOSED DESIGN FACTORS FOR CFRP STRENGTHENED CONDITIONED BEAM

In this study a reduction factor, $Ø_u$ is proposed to predict the bending strength of conditioned beams for 3 months and 6 months conditioning period from experimental results. It has been observed that the ultimate load carrying capacity of the conditioned beams has reduced compare to corresponding control specimens. The reduction factors are obtained as the ratios of the ultimate load of conditioned beams to the corresponding control beam which are 0.99, 0.95, 0.95 and 0.97 for beams S4A-3, S5A-3, S4B-3 and S5B-3. The maximum reduction factor $Ø_u$ = 0.95 is proposed for CFRP strengthened tubular steel hollow beam with epoxy treated surface and for the conditioning period of 6 months.

CONCLUSION

In this study, the satisfactory potential of CFRP fabrics for enhancing strength, stiffness and ductility of strengthened circular hollow sections (CHS) members has been noticed. In addition, adhesion promoter was found to enhance the bond between CFRP and steel substrate and durability under cold weather. From the study conducted, the following conclusion can be drawn:

(1) The CFRP reinforced control beams showed higher ultimate load than that of bare specimen B2. Likewise all the conditioned beams having treated and untreated surface showed higher ultimate load than control beams. In addition, the control and conditioned specimens having epoxy treated surface performed better in terms of ultimate strength than untreated beams. It likely happens due to superior bond attributed by adhesion promoter applied on sand blasted steel surface which is considered as treated surface.
(2) The strengthened control beams, S4B-1 and S5B-1 appeared as stiffer than bare one. In plastic region, the epoxy treated surface control and cured beams showed stiffer behaviour than the beams with untreated surface with an exception for beam S5B-3 for a very short period of loading duration.
(3) Typical ductile mode of failure was observed for bare specimen as well as strengthened specimens. The bare beam showed more ductile behaviour but it was lesser stiff than strengthened control as well as conditioned beams. Both the control and conditioned CFRP strengthened beams showed no serious deboning until yielding of the steel.
(4) The proposed design factors of conditioned beams to calculate ultimate load is found as 0.95. However, this factor reflects only effect of short term exposure to low temperature on performance of the system.

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REFERENCES

Al-Shawaf, A., Al-Mahaidi, R. and Zhao, X. (2008). "Effect of elevated temperature on bond behaviour of high modules CFRP/steel double-strap joints", *Australasian Structural Engineering Conference (ASEC),* Melbourne, Australia, 26-27 June.

Dawood, M. and Rizkalla, S. (2010). "Environmental durability of a CFRP system for strengthening steel structures", *Construction and Building Materials*, 24, 1682-1689.

Fawzia, S. (2013). “Evaluation of shear stress and slip relationship of composite lap joints”, C*omposite Structures*, 100, 548-553.

Fawzia, S., Zhao, X.L. and Al-Mahaidi, R. (2010). “Bond-slip models for double strap joints strengthened by CFRP”, *Composite Structures*, 92(9), 2137-2145.

Fawzia, S., Al-Mahaidi, R., Zhao, X.L. and Rizkalla, S. (2007). “Strengthening of circular hollow steel tubular sections using high modulus CFRP sheets”, *Construction and Building Materials*, 21(4), 839-845.

Gamage, J. C. P. H., Mahaidi, R. Al and Wong, M. B. (2009). "Durability of CFRP-strengthened concrete members under extreme temperature and humidity", *Australian Journal of Structural Engineering, 9* (2),111-118.

Haedir, J., Bambach, M. R., Zhao, X. L. and Grzebieta, R. H. (2009). "Strength of circular hollow sections (CHS) tubular beams externally reinforced by carbon FRP sheets in pure bending", *Thin-walled structures*, 47 (10), 1136-1147.

Seica, M. V. and Packer, J. A. (2007). "FRP materials for the rehabilitation of tubular steel structures, for underwater applications", *Composite Structures* 80 (3), 440-450.

Smith, S. T., Kaul, R., Ravindrarajah, R. and Otoom, O. M. A. (2005). "Durability Considerations for FRP-strengthened RC Structures in the Australian Environment", *Australian Structural Engineering Conference*, Sydney, N.S.W, edited, 952-961, Engineers Australia.